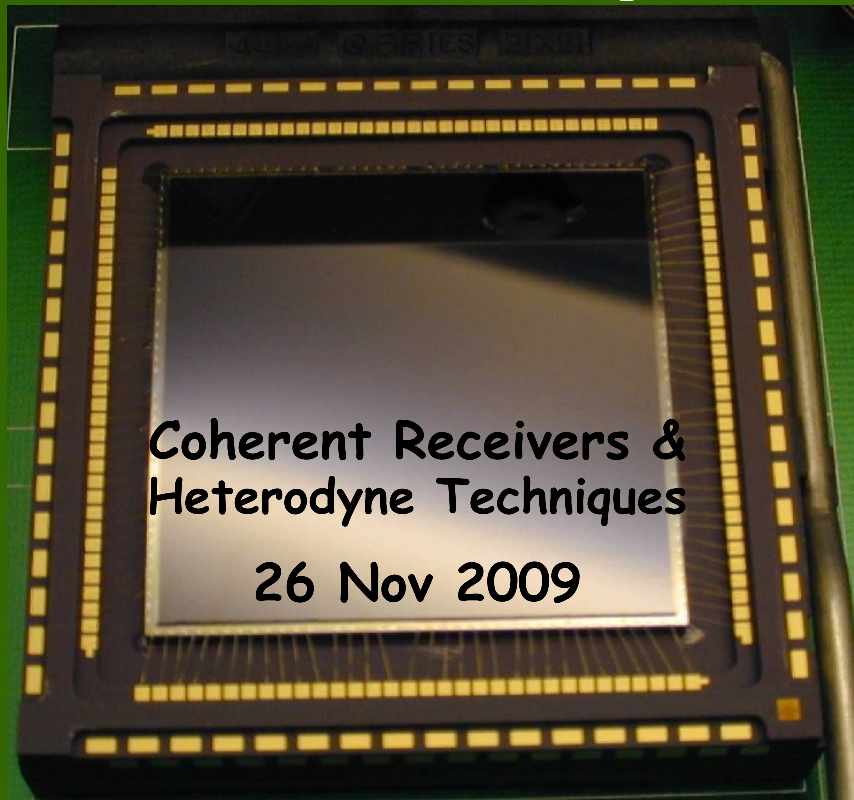
Detection of Light



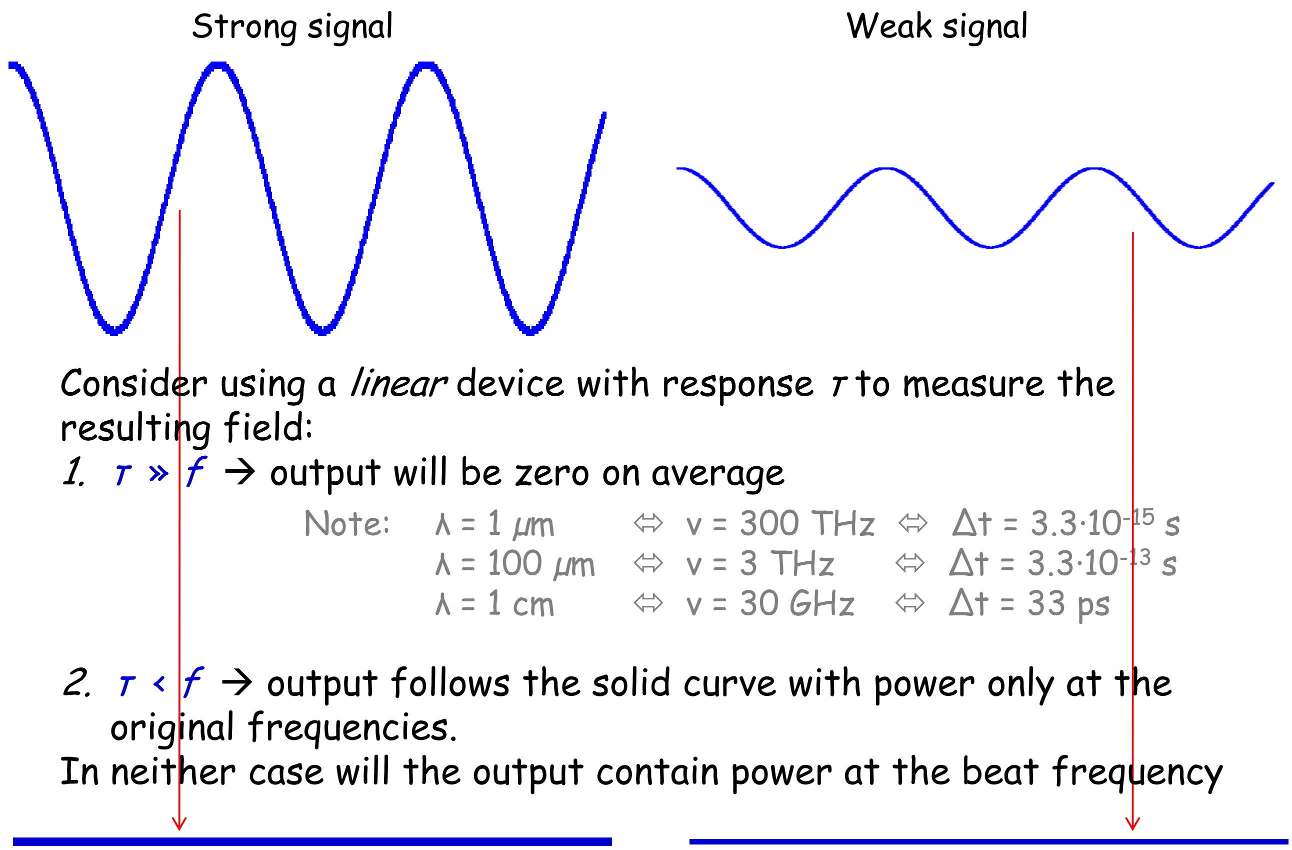
See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

Remember: three general types of detectors:

1. Photon detectors (e.g., photoconductors, photographic plates)
2. Thermal detectors (e.g., bolometers)
3. Coherent (heterodyne) receivers

Basic Principle of Coherent Detection

Problem of Wave Detection



Consider using a *linear* device with response τ to measure the resulting field:

1. $\tau \gg f$ → output will be zero on average

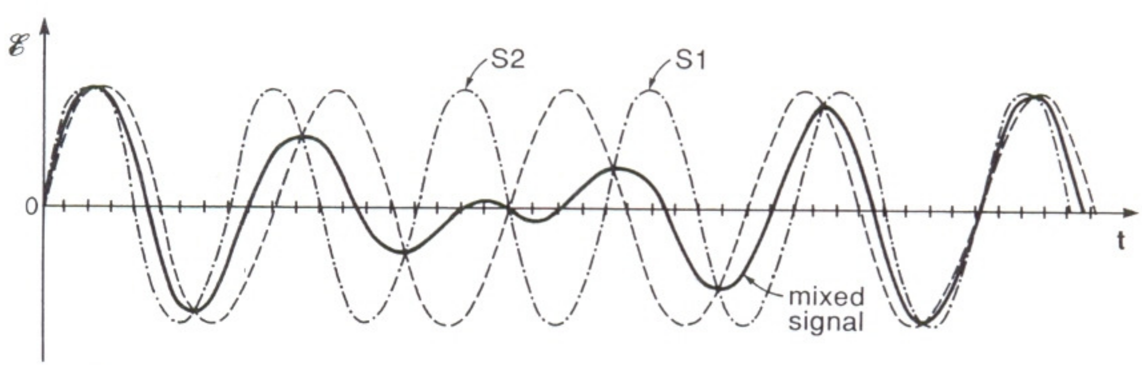
   Note: $\lambda = 1\ \mu m$ ⇔ $\nu = 300$ THz ⇔ $\Delta t = 3.3 \cdot 10^{-15}$ s
   $\lambda = 100\ \mu m$ ⇔ $\nu = 3$ THz ⇔ $\Delta t = 3.3 \cdot 10^{-13}$ s
   $\lambda = 1$ cm ⇔ $\nu = 30$ GHz ⇔ $\Delta t = 33$ ps

2. $\tau < f$ → output follows the solid curve with power only at the original frequencies.

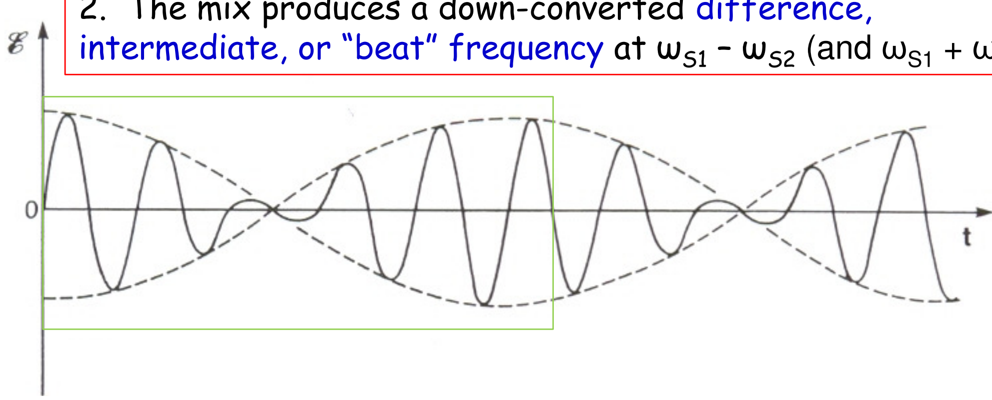
In neither case will the output contain power at the beat frequency

Solution (1): Down-convert the Frequency

1. The signal S_1 is mixed with a local oscillating field S_2

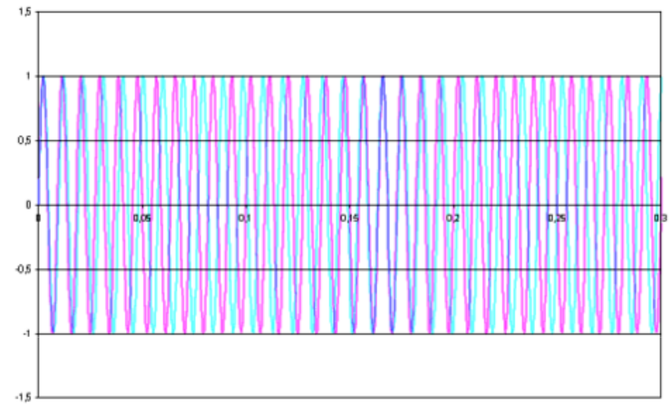


2. The mix produces a down-converted difference, intermediate, or "beat" frequency at $\omega_{S1} - \omega_{S2}$ (and $\omega_{S1} + \omega_{S2}$).

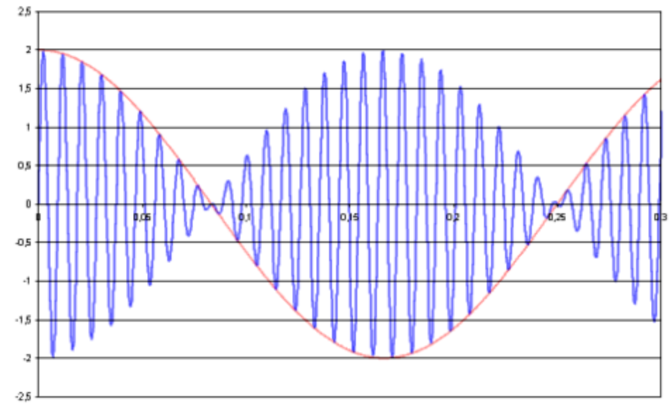


The Intermediate Frequency (IF)

The IF is the "beat frequency", the difference frequency between local oscillator and signal frequency.



Example: To measure a signal at 1.5 GHz one could use an oscillator at 1.55 GHz, which would down-convert the signal to a 50 MHz carrier.



Basic Principle of Mixing

Heterodyne* receivers mix signals of different frequencies.

→ resulting signal contains only frequencies from the two original signals

→ could (in principle) preserve the phase information

→ amplitude is modulated at the difference frequency ("beat frequency")

Heterodyne receivers measure this modulated amplitude.

Consider two waves, x_1 and x_2: $x_1(t) = A_1 \sin(2\pi\omega_1 t)$

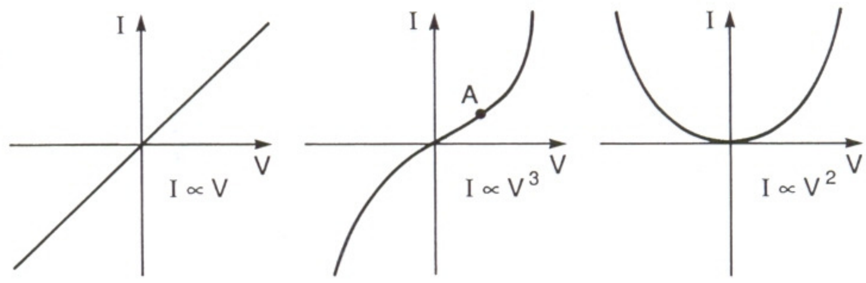
and "mix" them: $x_1(t)x_2(t) = A_1 \sin(2\pi\omega_1 t) A_2 \sin(2\pi\omega_2 t) =$

(using the trigonometric identity) $= A_1 A_2 \frac{1}{2}\left[\underbrace{\cos 2\pi(\omega_1 - \omega_2)t}_{\text{difference}} - \underbrace{\cos 2\pi(\omega_1 + \omega_2)t}_{\text{sum}}\right]$

*The word *heterodyne* is derived from the Greek roots *hetero-* "different", and *-dyne* "power".

Solution (2): Use a non-linear Device

A linear device (a) yields no output power at any frequency.



(a) linear (b) cubic (c) quadratic

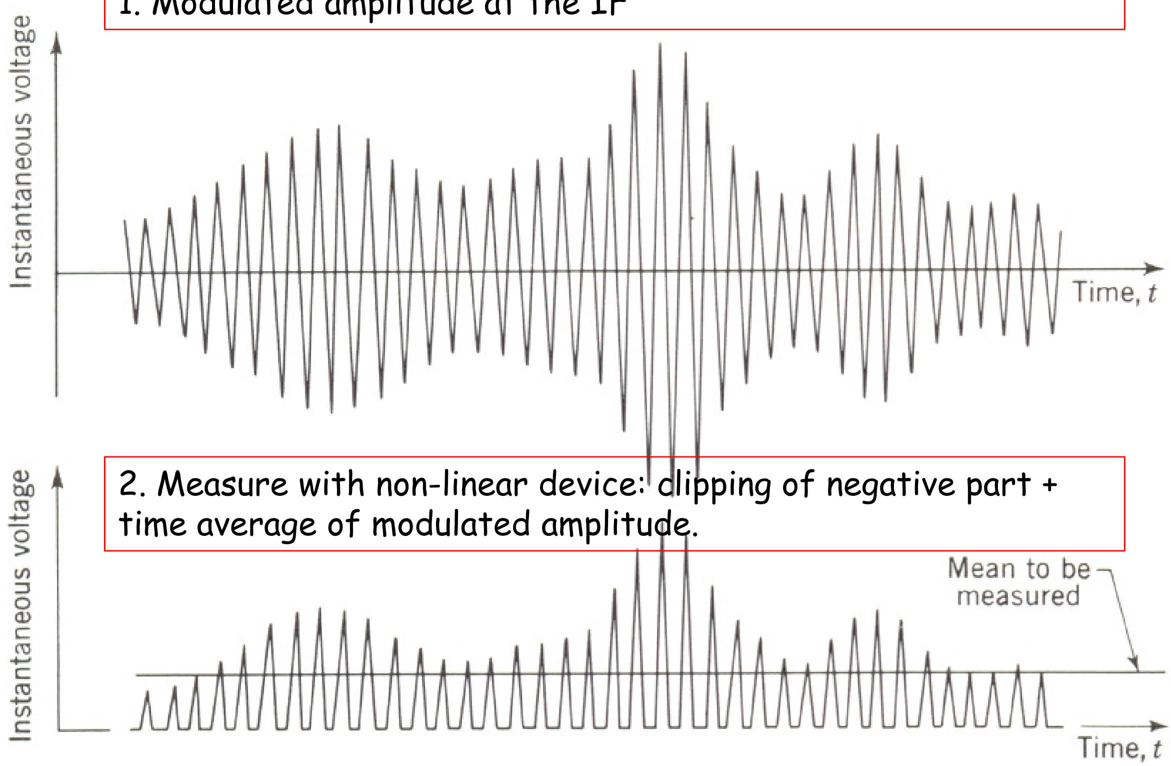
➔Need a non-linear device (b,c) that converts power from the original frequencies to the beat frequency = mixer)

- sub-mm & radio → the mixer is usually a diode.
- visible & infrared → the mixer is a photon detector ("photomixer") .

Measurement of the Signal

1. Modulated amplitude at the IF

2. Measure with non-linear device: clipping of negative part + time average of modulated amplitude.



Advantages and Applications

Advantages:

- Directly encodes the spectrum of the incoming signal over a wide wavelength range → ideal for spectroscopy
- Wavefront reconstruction → (VLB-)interferometry
- Weak signals (typically power(ω_{LO}) » power(ω_S)) → amplification of strong oscillator signal
- Signals are down-converted to frequencies where low-noise electronics can be used.

Applications:

- Monopolized the radio regime
- Common in sub-mm receivers
- Less used at optical/IR wavelengths because of narrow $\Delta\lambda$, FOV, problem to construct large arrays, and noise due to the "quantum limit".

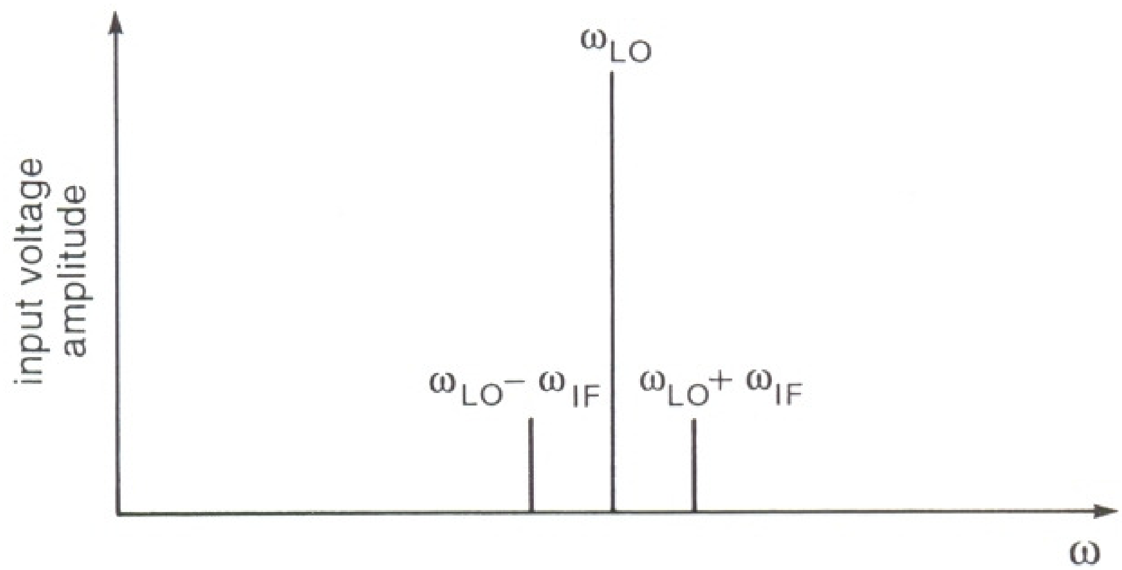
The Sidebands

Two Sidebands !

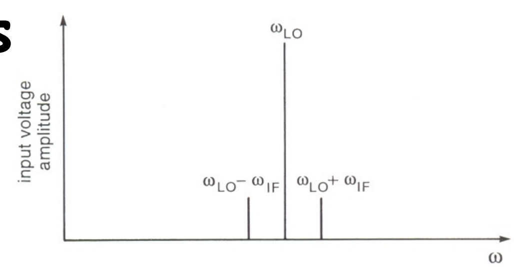
Before we stated: The mix produces a down-converted difference, intermediate, or "beat" frequency at $\omega_{S1} - \omega_{S2}$.

Unfortunately, from the measured IF signal one cannot tell whether the signal frequency ω_S is slightly lower or higher than ω_{LO}.

Hence, one assumes that the signal contains two components of equal strength, one at $\omega_{LO} + \omega_{IF}$ and one at $\omega_{LO} - \omega_{IF}$



Sideband Problems



Gain: signal has been down-converted to much lower frequency than ω_S

Loss: we don't know if $\omega_S > \omega_{LO}$ or $\omega_{LO} > \omega_S$

Is this a problem?

- for continuum sources – not really
- for spectral lines – yes!
    - tuning the mixer
    - "image rejection" narrowband filter in front of receiver

    → single sideband

The Bandwidth

The IF Bandwidth Δ_{IF}

The bandwidth Δf_{IF} (even of the best photodiode mixers) is usually small compared to the signal frequency – a fraction to a few percent.

Heterodyne receivers operating at short wavelengths have poor S/N on continuum sources.

→ Heterodyne techniques are best for measuring spectral lines at extremely high resolution.

Note: in case the bandwidth Δf_{IF} is sufficiently wide the IF output can be sent to a set of parallel narrowband filters ("filter bank") → spectral multiplexing

The time response of a heterodyne receiver is $1/f_{IF}$ and can be as short as a few nanoseconds.

IF Bandwidth

The IF bandwidth Δf_{IF} depends on:

1. frequency response of the mixer
2. signal amplifier
3. signal filter

τ_{RC} of photoconductor mixers could be short, but are often limited by recombination times:

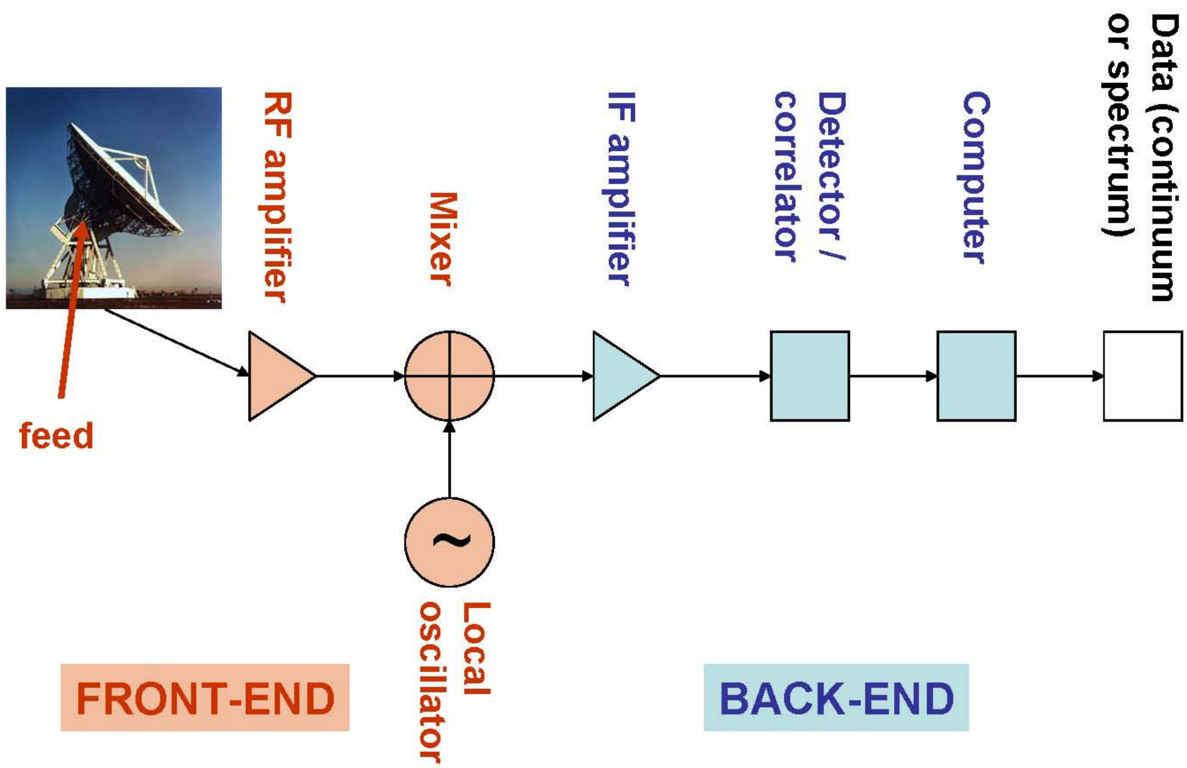
- for Ge: $\Delta f_{IF} < 10^8$ Hz
- for InSb (hot electron bolometers): $\Delta f_{IF} < 10^6$ Hz

Δf_{IF} of photodiode mixers are usually smaller ($\Delta f_{IF} <$ few$\cdot 10^9$ Hz), in particular in the infrared:

- at 10µm $\nu = 3\cdot 10^{13}$ Hz
- but even if $\Delta f_{IF} \sim 10^9$ Hz the bandwidth is only 0.01% of λ
- at 3mm $\nu = 10^{11}$ Hz $\rightarrow \Delta f_{IF} \sim 3\cdot 10^9$ Hz $\rightarrow$ 6% of λ

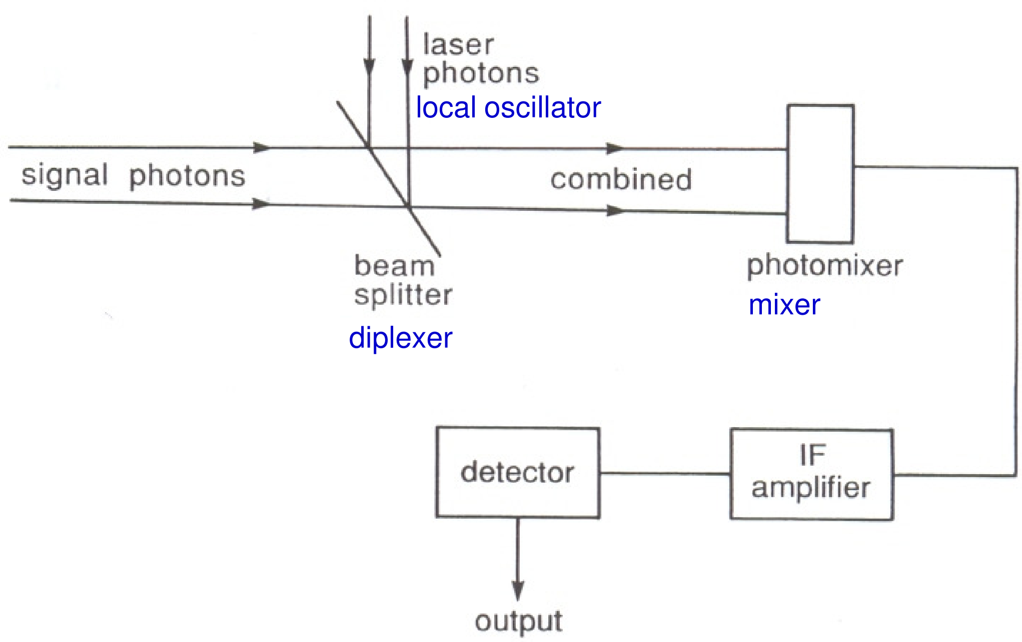
System Overview

Setup of a Coherent Detection System (1)



taken from Sandor Frey's Summer School presentation at
http://www.vlti.org/events/assets/4/documents/RadioInterferometry-Frey.pdf

Setup of a Coherent Detection System (2)



Note the order:

Signal+LO → Photomixer → IF amplifier → Detector → Output

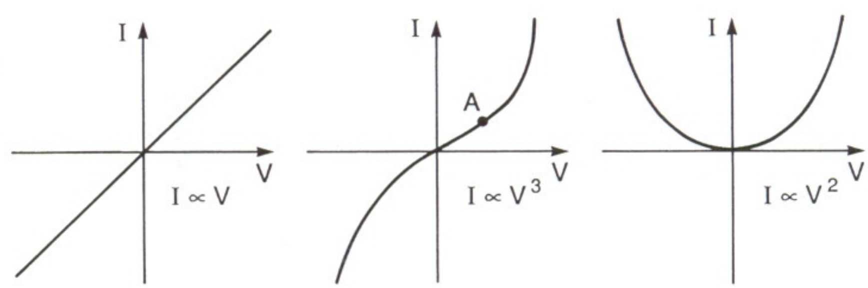
"Detector" here is *not* the device that receives the signal photons but the output of the IF amplifier.

Key-Components

I. Mixers

Mixers

If the mixer is linear **(a)** the conversion efficiency is zero.



(a) linear **(b)** cubic **(c)** quadratic

Even if the mixer has an odd function of voltage around the origin **(b)** the conversion efficiency is zero.

But if biased above zero (→ **A**) the average change in current is larger for positive than for negative voltage peaks.

The best efficiency is achieved for an even function of voltage **(c)**.

If $I \sim V^2$ then output ~ (field strength)^2 ~ power which is exactly what we want to measure!

Mixers (2)

Generally, a useful mixer has an I-V curve than can be approximated by a Taylor series around the operating point V_0:

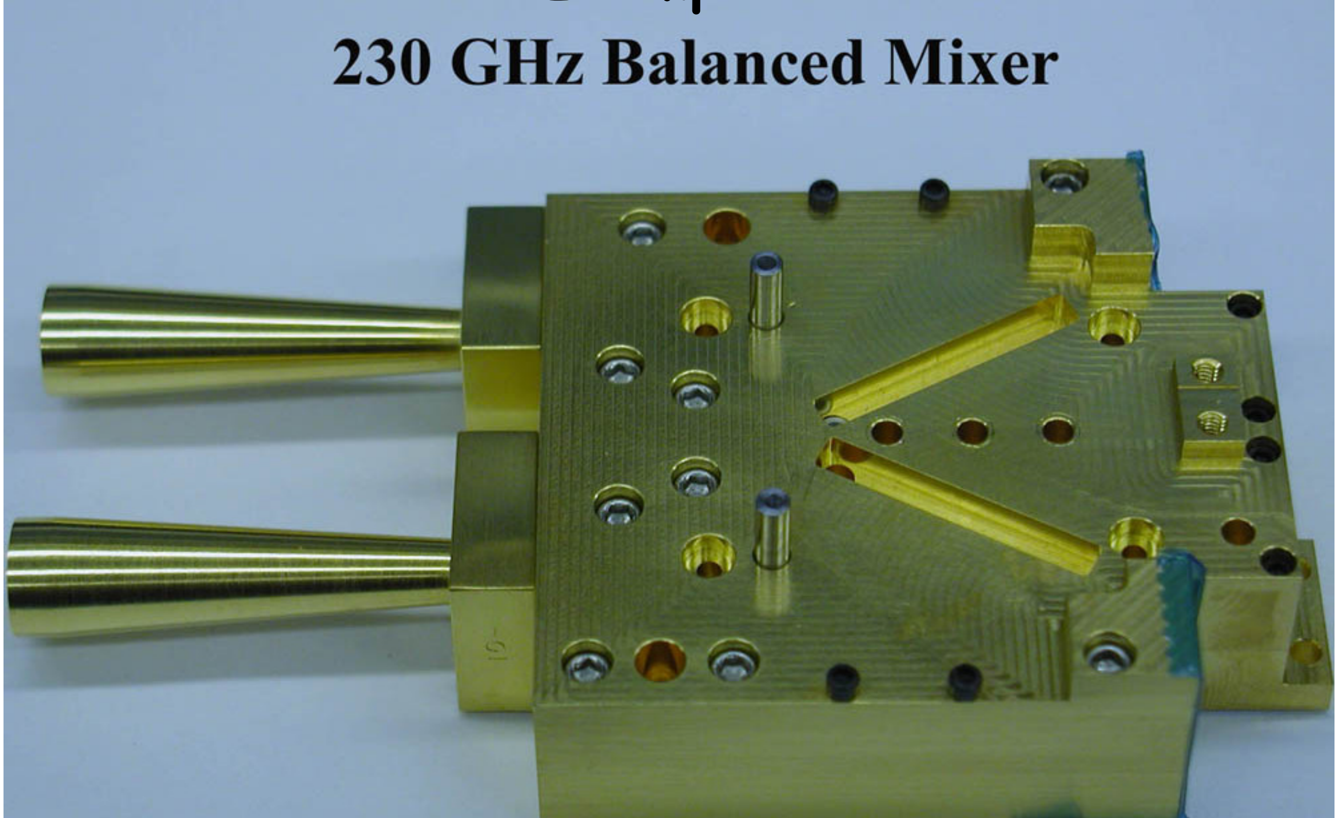
$$I(V) = \underbrace{I(V_0)}_{\text{DC}} + \underbrace{\left(\frac{dI}{dV}\right)_{V=V_0} dV}_{\text{zero response}} + \underbrace{\frac{1}{2!}\left(\frac{d^2 I}{dV^2}\right)_{V=V_0} dV^2}_{\text{square-law mixer}} + \underbrace{\frac{1}{3!}\left(\frac{d^3 I}{dV^3}\right)_{V=V_0} dV^3 + \frac{1}{4!}\left(\frac{d^4 I}{dV^4}\right)_{V=V_0} dV^4 + \ldots}_{\text{negligible if } dV = V - V_0 \text{ is small}}$$

We could use a diode* as mixer: $I = I_0\left(e^{qV_B/kT} - 1\right)$ (diode equation – 15 Oct)

Exponential can be expanded as: $$e^{qV_B/kT} - 1 \approx \underbrace{\frac{qV_B}{kT}}_{\text{DC}} + \underbrace{\frac{1}{2}\left(\frac{qV_B}{kT}\right)^2}_{\text{zero response}} + \ldots$$

- a diode is non-linear
- non-linear means that its response I is not proportional to the input V
- if $I \sim V^2 \sim \bar{E}^2 \sim P$ that's exactly what we want!

Examples



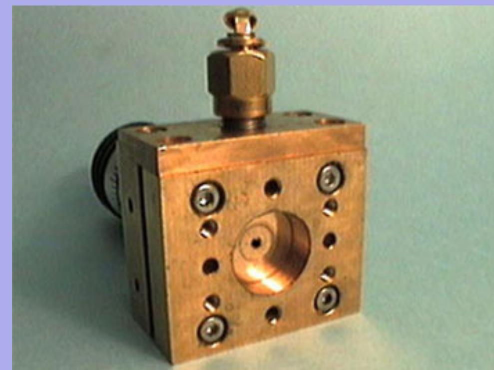
Mixer Block Hardware of the 180-280 GHz Balanced Mixer
http://www.submm.caltech.edu/cso/receivers/

Examples (2)

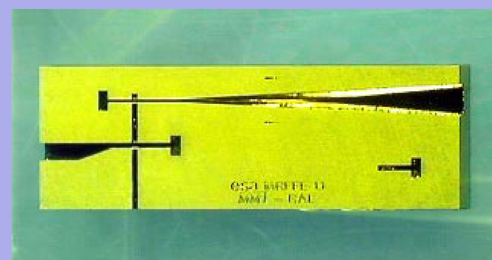
SIS front-end receiver for balloon heterodyne receiver TELIS

183 GHz fixed-tuned sub-harmonic mixer

Figures from the MMT website of the Rutherford Appleton Lab:
http://www.sstd.rl.ac.uk/mmt/components_mixers.php



2.5THz Schottky diode mixer



560 GHz micro-machined sub-harmonic mixer

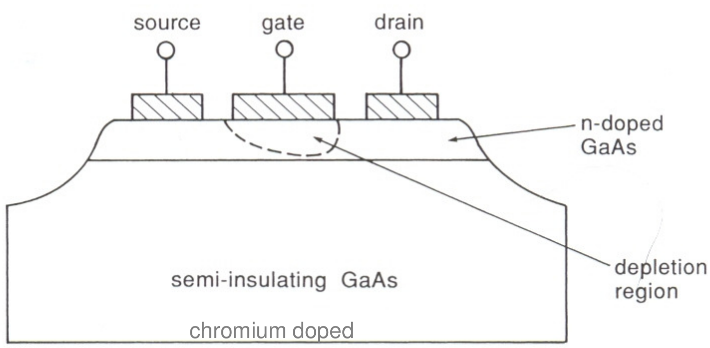
Key-Components

II. IF Amplifiers

IF Amplifier (1)

Amplifiers are based on metal-semiconductor field-effect transistors (MESFETs) [similar to JFETs but using a Schottky junction].

MESFET



Can be made very small
→ short electron transit times.

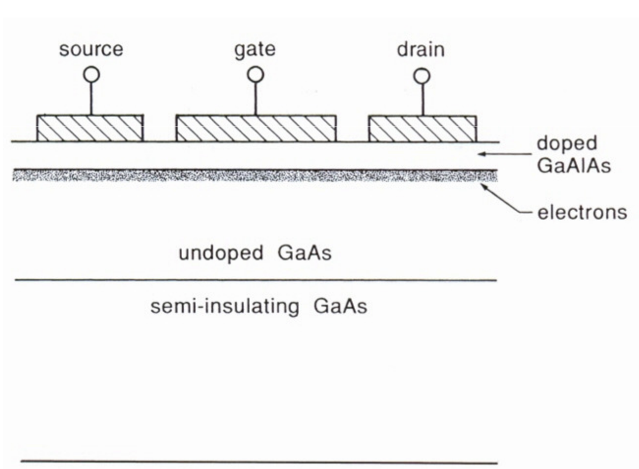
Problem: smaller size
→doping must increase
→reduced mobility (scattering)

Chromuim doping places EF in the middle between valence and conduction band → "semi-insulator".

IF Amplifier (2)

Because of the low power in the IF signal, the amplifier following the mixer is critical.

Best performance: high electron mobility transistors (HEMTs) on GaAs or InP up to ~ 10^{11} Hz.



HEMT setup:

MESFET grown on heavily doped GaAlAs over GaAs.

E_F of GaAlAs can be above E_c of GaAs

→ electrons gather in thin GaAs layer where the mobility is high

Key-Components

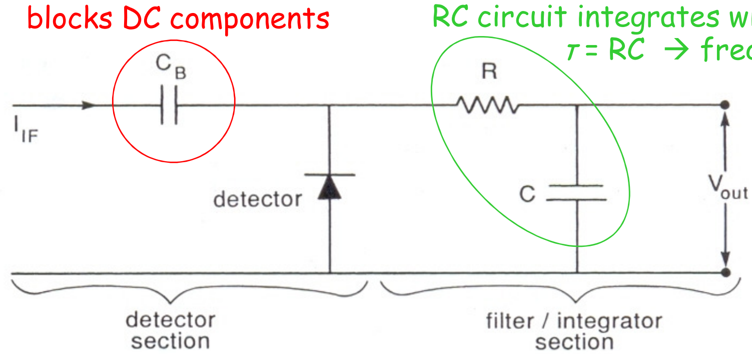
III. Detectors

Detector Stage (1)

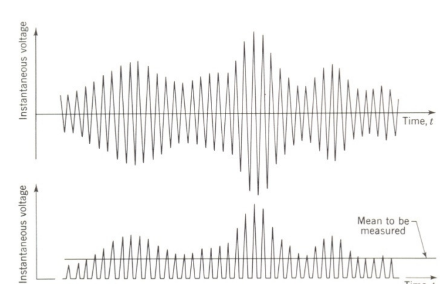
The detector rectifies the signal and sends it through a low-pass filter. Hence it converts the signal to a *slowly* varying output

blocks DC components

RC circuit integrates with time constant $\tau = RC$ → frequency smoothing



If operated at zero bias ($I \ll I_0$) the 3rd and higher terms are negligible. → good square-law detector.



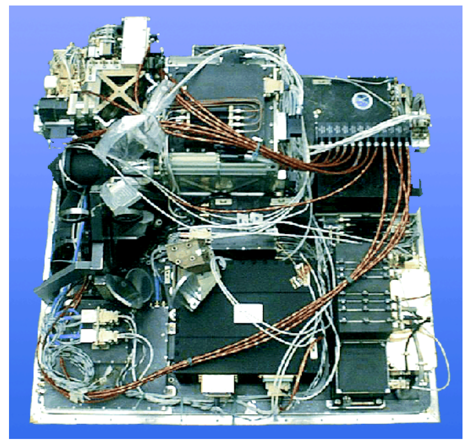
Detector Stage (2)

If the IF signal contains important frequency components it should *not* be smoothed directly.

Instead, the signal can be sent to a bank of narrow-band electronic filters, operating in parallel – with a smoothing detector for each filter output.

Hence, the filter bank can provide a spectrum of the source. (A back-end spectrometer could consist of several filters tuned to different frequencies with detectors on their outputs.)

This spectral multiplexing is one of the most useful features of heterodyne receivers.

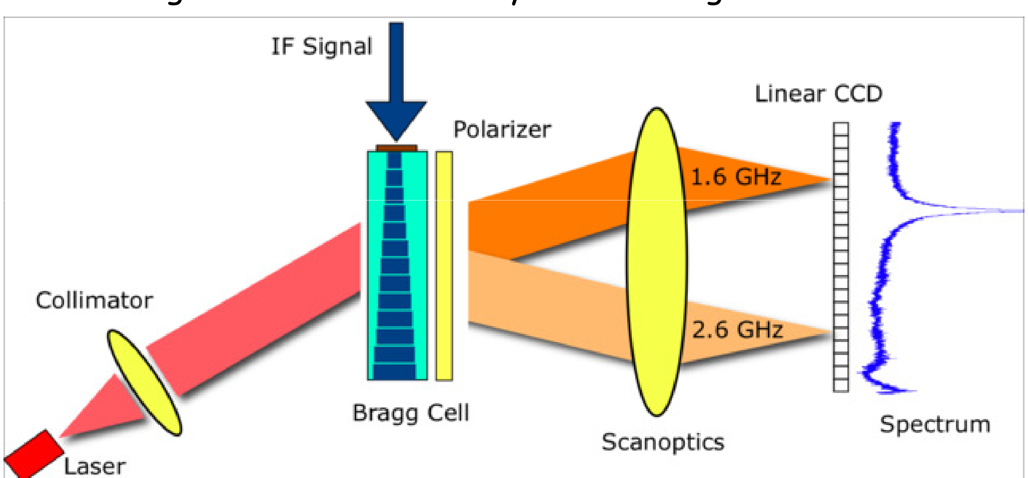


Autocorrelator with filterbank [Odin satellite (U. Frisk et al. 2003)]

Acousto-Optical Spectrometer

Often the spectrometer includes a digital auto-correlator or an acousto-optical spectrometer (AOS).

An AOS converts the frequencies to ultrasonic waves that disperse a monochromatic light beam onto an array of visible light detectors.



from Wikipedia

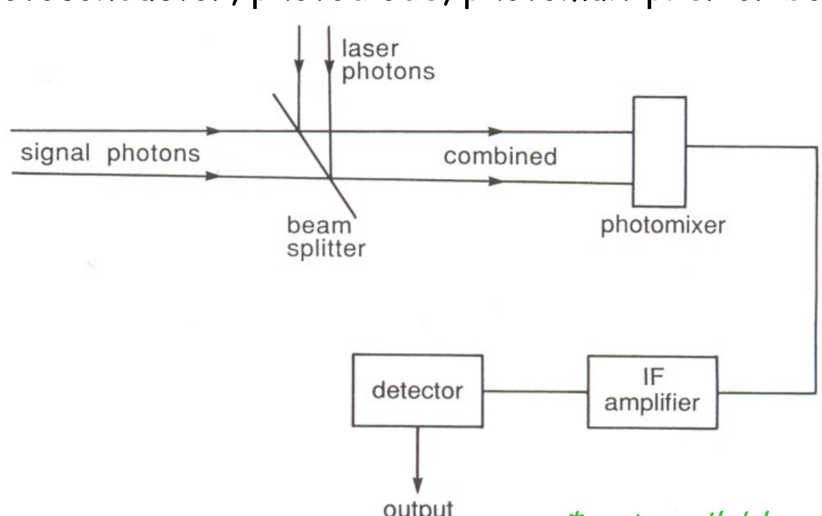
The acoustic wave can be created in a crystal ("Bragg-cell") and modulates the refractive index. induces a phase grating. The angular dispersion is a measure of the IF-spectrum.

Optical Heterodyne Receivers

Opt/IR Heterodyne Receivers

Opt/IR heterodyne receivers...:

- must operate in double sideband
- use a continuous wave (CW) laser* as local oscillator
- use a beam splitter ("diplexer") to combine signal and laser
- use a photoconductor, photodiode, photomultiplier or bolometer as mixer



* not available at all wavelengths!

Conversion Gain

Previously, photon detectors with time constants of milli-seconds to seconds have been satisfactory. Now we need mixers responding up to 1 GHz or more.

The output current is $I(t) = I_{LO} + I_S + 2\sqrt{I_{LO} I_S} \cos[(\omega_S - \omega_{LO})t + \Phi]$

where Φ is the relative phase difference between the signal and LO fields. (Detailed mathematical treatment see Rieke book p. 279ff.)

The IF current is the heterodyne signal and has a mean-square amplitude of:

$$\left\langle I_{IF}^2 \right\rangle_t = 2 I_{LO} I_S$$

The conversion gain is: $\Gamma \equiv \dfrac{\text{deliverable IF signal power}}{\text{input signal power}} = \left(\dfrac{\eta q}{h\nu}\right) G V_b$

Example: λ=10μm, η=0.5, G=0.5, V_b=5V → Γ_c = 10

Throughput

Throughput

Two factors limit the throughput of a heterodyne system:

1. Only components of the signal electric field vector parallel to the laser field can interfere (incl. polarization!)

2. A coherent receiver should operate at the diffraction limit of the telescope

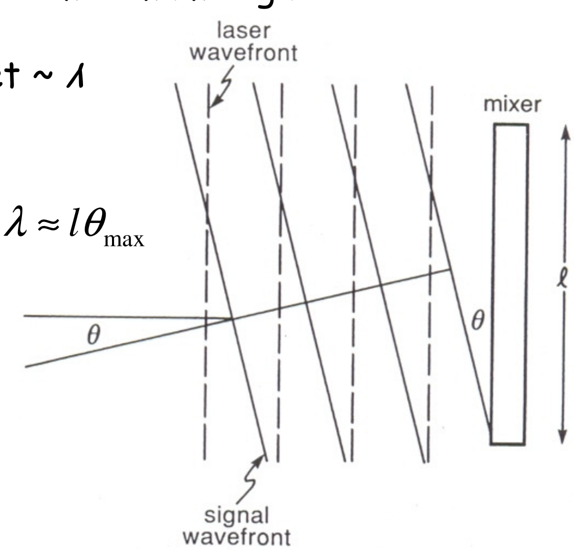
➔ "Antenna theorem" (applies to all heterodyne detectors)

Throughput – Factor 1

The signal beam will strike the mixer in a range of angles relative to the LO / laser beam.

The conditions for interference limit the maximum angular displacement.
Full cancellation occurs when the offset ~ λ

$$l \sin \theta_{max} = \lambda \approx l \theta_{max}$$



Since the LO / laser field is polarized only one polarization component of the source can interfere and produce a signal
→ heterodyne receivers = single-mode detectors

Throughput – Factor 2

From $l \sin\theta_{max} = \lambda \approx l\theta_{max}$ and with $\Omega = 4\pi \sin^2(\theta/2) \rightarrow \theta^2 \approx \Omega$ we get:

$$A\Omega \approx \lambda^2$$

The throughput `$A\Omega$' (collecting area times field of view FOV) is also called the Etendue and is *invariant in any aberration-free optical system*.

Therefore, $A\Omega$ sets also a constraint on the beam that can be accepted by a telescope of diameter D (or any other optical system).

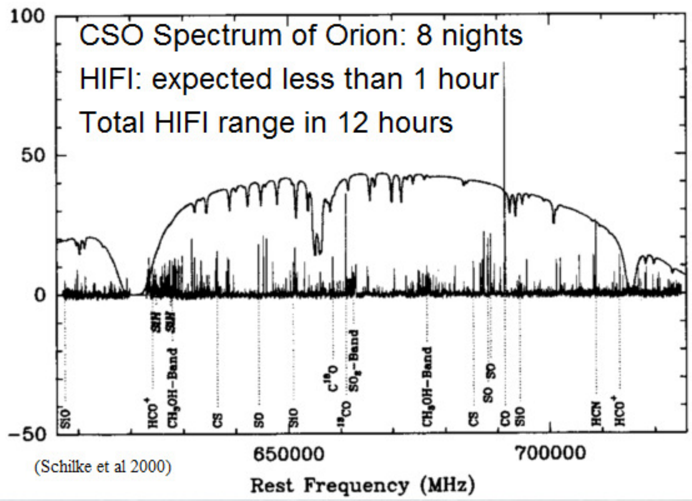
The angular diameter of the FOV on the sky is: $\Phi \approx \frac{\lambda}{D} \approx \text{Rayleigh criterion}$

A coherent receiver should operate at the diffraction limit of the telescope.
[If the receiver only accepts a smaller FOV there is significant loss; if the receiver accepts much more → higher background and Factor 1 limit.]

Examples: Herschel/HIFI et al.

HIFI on Herschel

- The observed frequencies range from 480 GHz (625μm) to 1920 GHz (156μm)
- Includes the [C II]158μm line
- Resolving power up to 10^7
- Each mixer is followed by a dedicated IF preamplifier
- the down-converted ω_{IF} is centered at 6 GHz
- $\Delta\omega_{IF}$ = 4 GHz



(Schilke et al 2000)

$$d\lambda = \frac{c}{\nu^2} d\nu = \frac{3\cdot 10^8 m/s}{(1920\cdot 10^9 Hz)^2} 4\cdot 10^9 Hz = 0.33\mu m$$

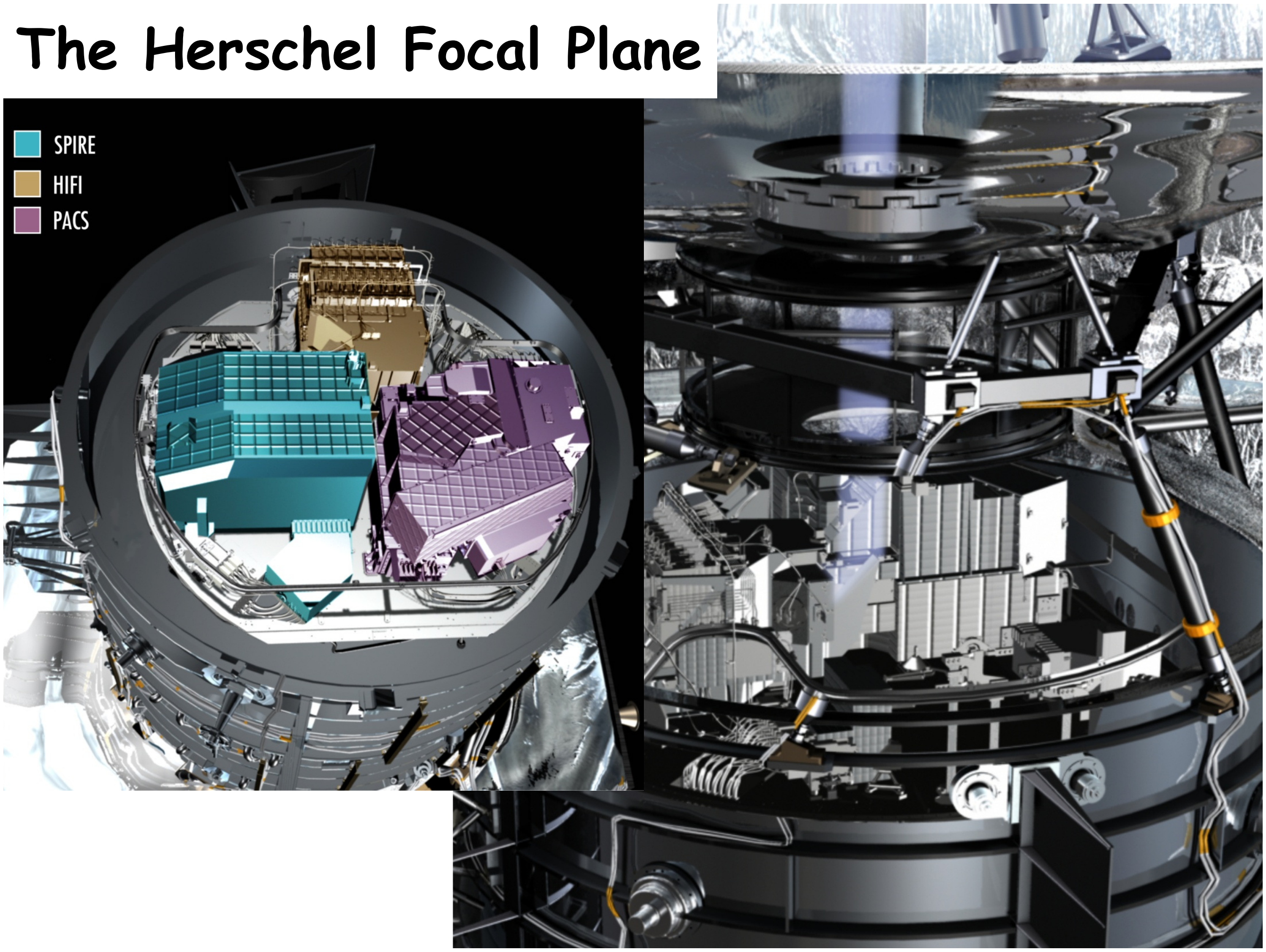
The HIFI Bands

	SIS Technology					HEB Technology	
GHz:	480 → 626	626 → 799	799 → 949	949 → 1108	1108 → 1280	1421 → 1691	1691 → 1911
HIFI Bands	1	2	3	4	5	6	7
μm:	612 → 473	473 → 375	375 → 313	313 → 271	271 → 240	208 → 178	178 → 157

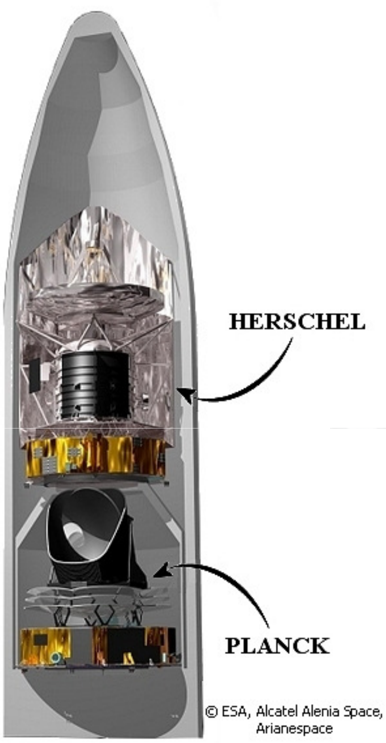
- Seven bands
- Two polarization components each
- Each band has a:
  - wide-band spectrometer (acousto-optical spectrometer)
  - high-resolution spectrometer (auto-correlator spectrometer)

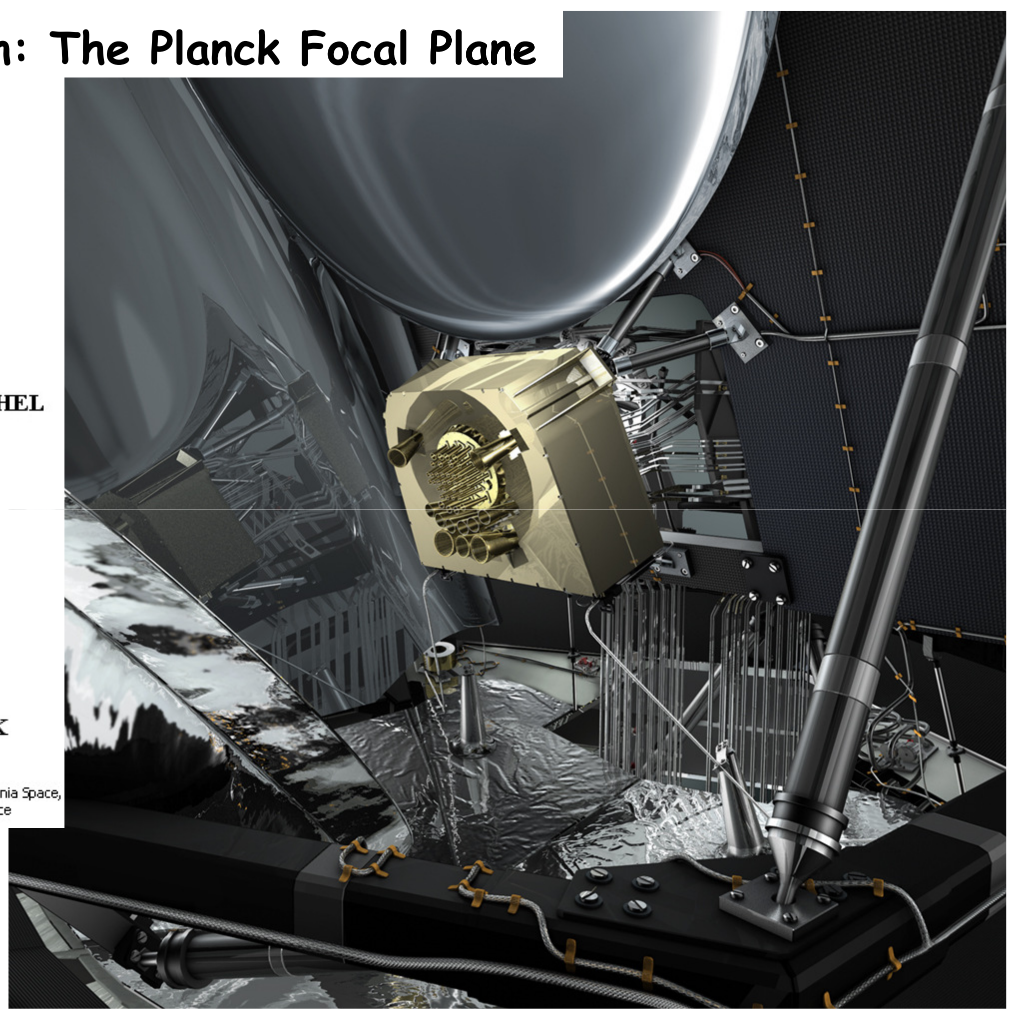
Wide Band Spectrometer Acousto-Optical Spectrometer	4 x 4 GHz sections	1 MHz (0.6 km s-1 @ 480 GHz)
High Resolution Spectrometer Digital Auto-Correlator	2, 4 or 8 x 250 MHz sections (max 2 GHz bandwidth) - 550 MHz samplers	0.14, 0.28, 0.56, 1.0 (wide band mode) MHz

The Herschel Focal Plane

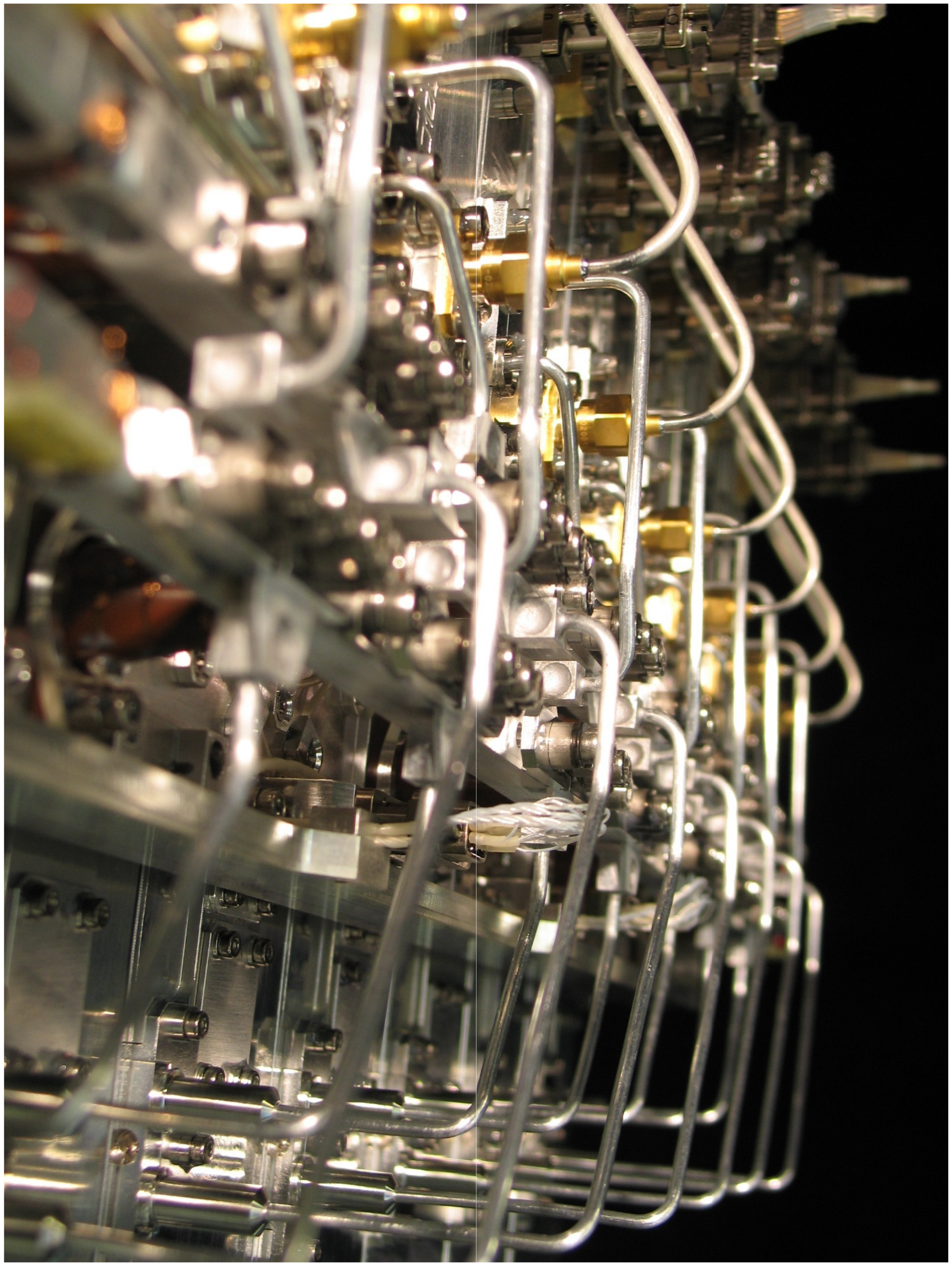
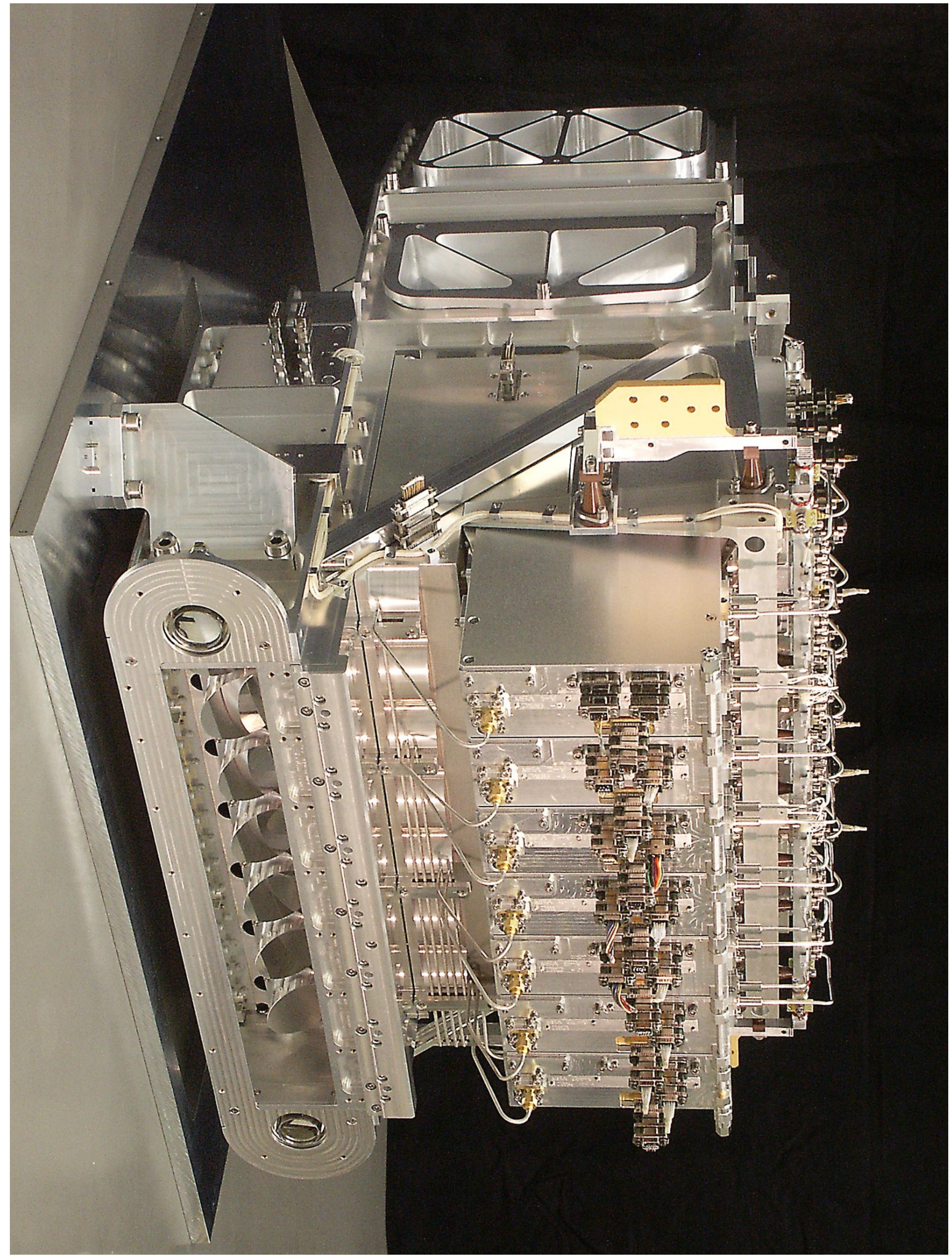


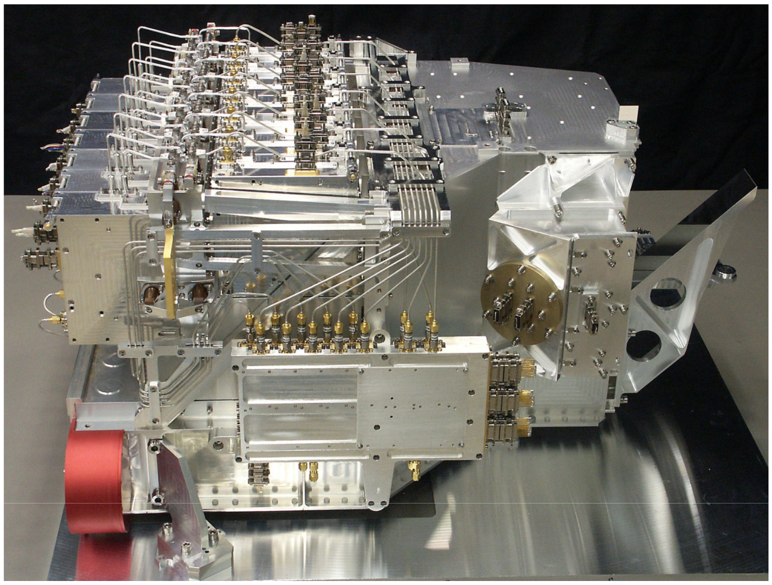
For comparison: The Planck Focal Plane

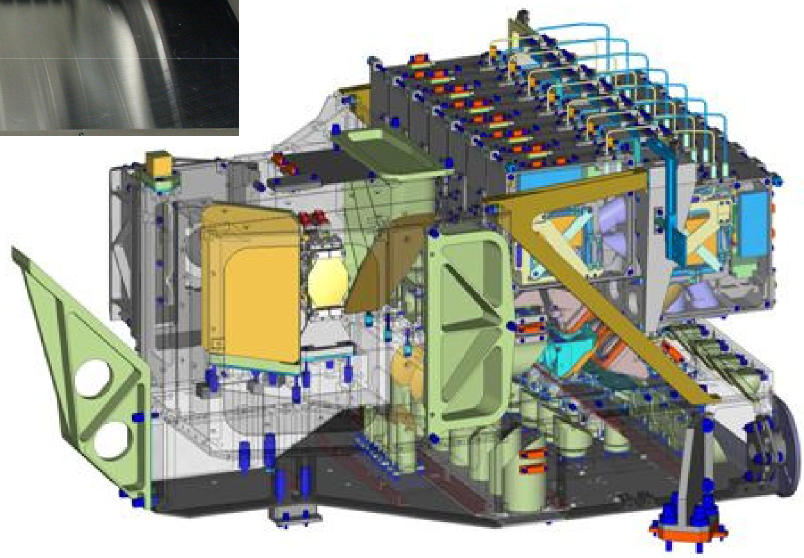




Planck - ESA's CMB experiment http://www.terahertz.co.uk/TKI/Planck/Planck_TK.html



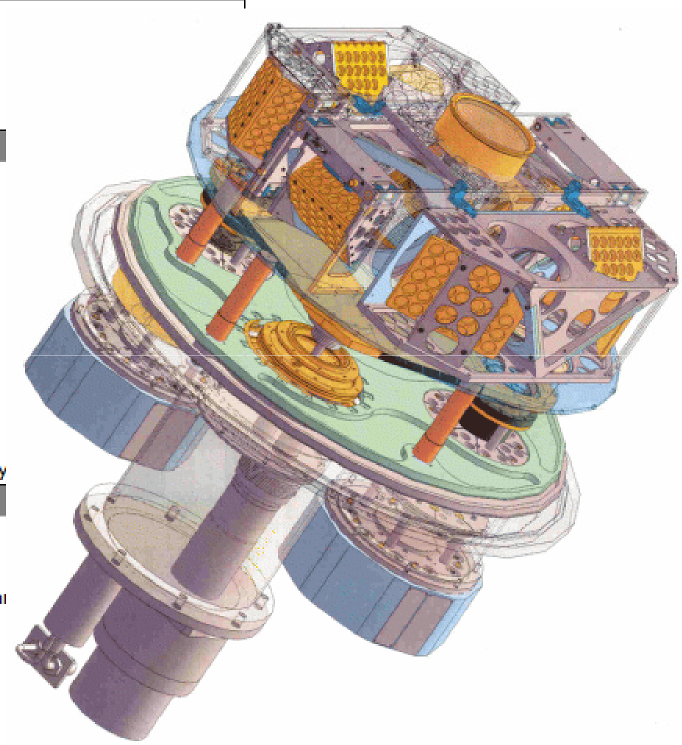


Champ+

A dual-frequency heterodyne submillimeter array receiver built jointly by MPIfR and NOVA/SRON/DIMES for APEX.

CHAMP+ Specifications (from proposal)

Telescope	APEX
Location	Llano de Chajnantor
Elevation	5000 m
Telescope Diameter	12 m
	Low-frequency band
Number of pixels	7 beams + 1 spare
Array configuration	2:3:2
RF range	602-720 GHz (ALMA band 9)
Beam size	9-7 arcsec
Mixer DSB noise temperature	<150-200 K
Expected T_{sys}	1000-1500 K
IF	2 GHz in the 4-8 GHz band
IF pass-band ripple	<3dB / 2 GHz
Polarization purity	>95%
Beam efficiency	>90% (Gaussian beam efficiency
	High-frequency band
Number of pixels	7 beams + 1 spare
Array configuration	2:3:2
RF range	790-950 GHz (ALMA band 10; la
Beam size	7-6 arcsec
Mixer DSB noise temperature	<350-400 K
Expected T_{sys}	1800-2500 K
IF	2 GHz in the 4-8 GHz band
IF pass-band ripple	<3dB / 2 GHz
Polarization purity	>95%
Beam efficiency	>90% (Gaussian beam efficiency)



http://www.strw.leidenuniv.nl/~champ/